6. Measurement uncertainty

The measurement uncertainty evaluation follows the procedure described in reference [7]. The individual uncertainty at each stage of the calibration is either of Type-A, evaluated using statistical methods, or Type-B, evaluated by other means[2]. The combined uncertainty is the root-sum-square of the individual uncertainty values. In the transfer technique calibration of heat-flux sensors, the measurement uncertainties accrue at two different stages. First, the uncertainty associated with the calibration of the transfer standard radiometer; and secondly, the uncertainty arising while calibrating the heat-flux sensor with the VTBB.

[2] Previous measurement data, experience, manufacturer's specification, other sources of data

6.1 Transfer standard radiometer

The uncertainty associated with the transfer standard radiometer calibration, discussed in Secs. 3 and 4.3, is a Type-B uncertainty and estimated to be 0.6 %.

6.2 VTBB temperature

The absolute temperature of the VTBB has no influence on the transfer technique calibration because the heat flux is determined independently from the radiometer measurements. It is only necessary that the blackbody temperature be stable over the time interval of the radiometer and test sensor measurements. The VTBB has a long-term stability within ± 0.1 K of the set temperature. The corresponding uncertainty in the radiant heat flux is 0.01 % at 1000 K and 0.004 % at 2773 K. This is negligible compared to the other uncertainties and can be ignored.

6.3 VTBB emissivity

The estimated emissivity of the VTBB is 0.99. However, the blackbody emissivity has no influence on the transfer calibration. Higher emissivity values result in realizing higher heat flux levels at the sensor surface for a given operating temperature.

6.4 VTBB radiation - aperture uniformity

The uniformity of radiation from the VTBB aperture has no major influence on the calibration because of identical effects on both the transfer standard and the test sensor. However, even with a uniformly radiating aperture, the irradiance distribution at the sensor location may not be uniform. This non-uniform distribution may require a correction to the measured responsivity of the sensor, as detailed in Sec. 6.7.

6.5 Alignment error (distance)

The location of the effective aperture of the VTBB is close to the heated end, about 8.5 cm inside the blackbody aperture with the short extension piece installed. The test sensor and the transfer standard radiometer are at a fixed distance from the blackbody aperture. Assuming a maximum error of about 0.2 mm in the location of the transfer standard radiometer and the sensor with respect to the reference plane, the corresponding uncertainty values will be 0.2 %, 0.14 % and 0.09 % at sensor locations corresponding to 12.7 mm, 62.5 mm, and 140 mm from the blackbody aperture, respectively. The uncertainty in the longitudinal location of the sensor translates into a corresponding change in the configuration factor (C_{fa}) between the radiating aperture and the sensor. Figure 6 shows the relative change in the configuration factor with respect to location of the sensor from the aperture [8]. At large distances, the irradiance varies inversely as the square of the distance from the aperture. Hence, the uncertainty in irradiance at the sensor will be approximately two times that due to positioning uncertainty. The corresponding uncertainty values for the irradiance are 0.4 %, 0.3 % and 0.2 % at sensor locations of 12.7 mm, 62.5 mm, and 140 mm, respectively.

6.6 Alignment error (angular)

The errors due to angular misalignment vary as the cosine of the angle. Assuming a maximum misalignment of about 2°, the corresponding uncertainty will be 0.06 %.

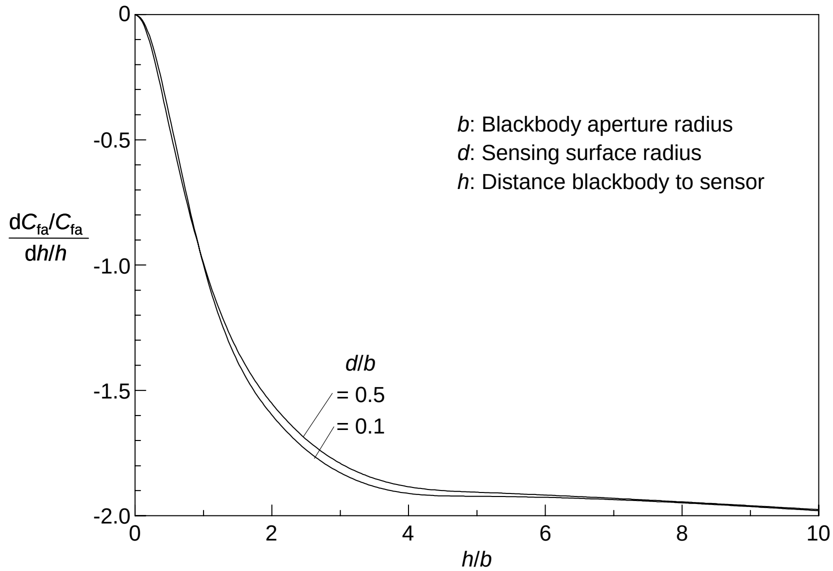

Figure 6. Incremental change in configuration factor with distance [8]

6.7 Radiometer aperture size

The areas on which radiant flux is incident on the transfer standard radiometer and the test sensor are different, and the heat-flux distribution in the test plane is not uniform. The distribution is a maximum at the center, and decreases away from the center. The sensitive area of the heat-flux sensor is generally small, and responds to the peak of the distribution. However, the aperture size of the transfer standard radiometer is much larger. Hence, the response of the transfer standard radiometer will be proportional to the average irradiance over the distribution.

Due to the averaging of the distribution over the aperture area, a correction to the radiometer measurement is necessary to determine the peak value of the distribution from the average reading. This peak value corresponds to the radiation incident on the sensor surface. The correction is a function of the sensor location from the blackbody aperture [8]. Figure 7 shows the calculated correction for different sensor dimensions as a function of sensor location from the blackbody aperture.

The correction factor is unity when the sensor is located at the aperture plane because of the uniform distribution. The correction peaks at a distance approximately equal to the radius of the aperture, and decreases asymptotically to unity at large distances. The correction is a strong function of the ratio of the sensor to the aperture radii. For the VTBB transfer calibration setup, a conservative value of the radiometer-aperture to sensor diameter ratio is about 0.44. The corresponding correction is less than 0.3 % of the measured radiometer reading. The correction increases rapidly when moving closer to the blackbody aperture. The uncertainty involved in evaluating this correction arises mainly from the difficulty of defining the exact position of the effective blackbody aperture. However, even with an uncertainty of about 5 % in the effective location, the corresponding uncertainty in the correction will be less than 0.05 %.

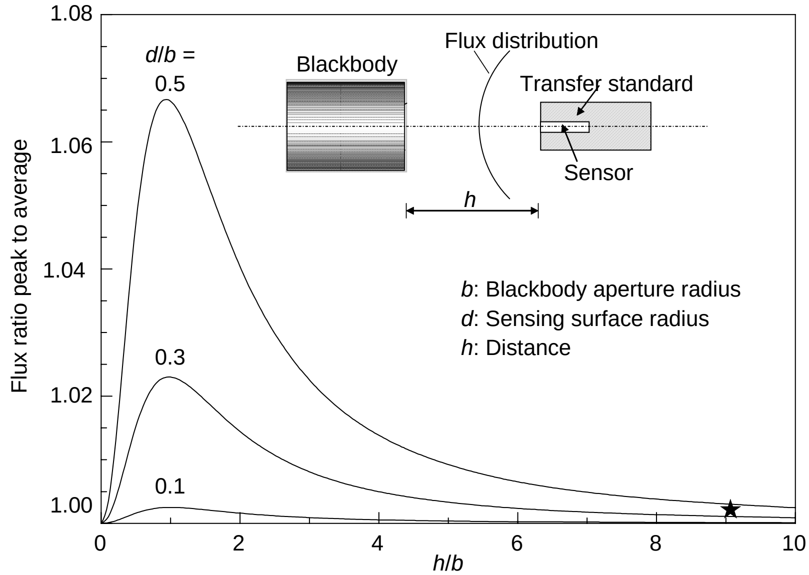

Figure 7. Ratio of peak to average irradiance at sensor location [8]

6.8 Radiometer/Sensor reading

The averaging times for the sensor and the radiometer measurements varies from 10 s to 60 s depending on the heat-flux level. If the sensors are water-cooled, longer averaging times are feasible. Figure 8 shows a typical variation of standard deviation of the mean (standard error) of the sensor output at two locations from the blackbody. The uncertainty will be a maximum of about 0.2 %, and will be much less at heat-flux levels greater than 10 kW/m^2.

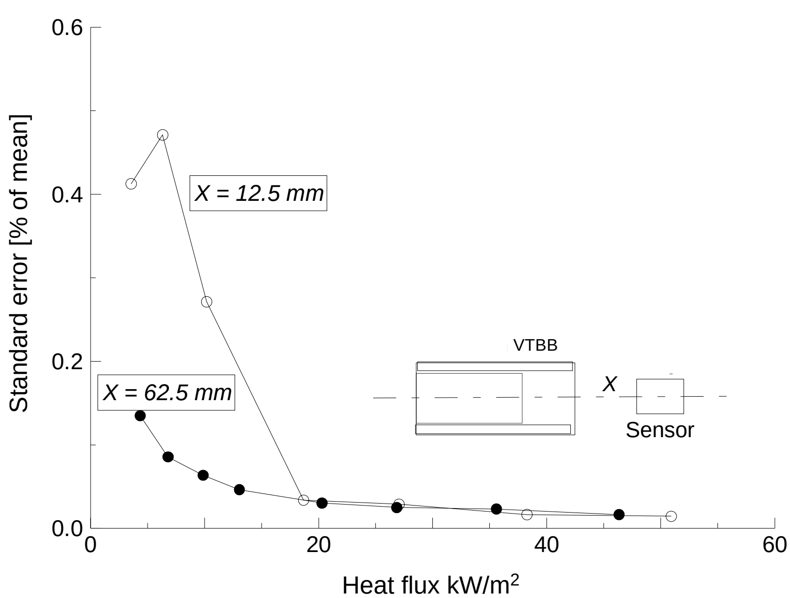

Figure 8. Standard deviation of the mean output for two sensor locations [1]

6.9 Other sources

The VTBB uses low-velocity argon gas flow to purge the cavity continuously during operation. The average exit-flow velocity is about 0.08 m/s. When the sensor is close to the cavity-exit, the low velocity jet impinging the sensor surface causes changes in the local heat transfer. This influence becomes smaller away from the exit because of jet spreading effects. The good agreement in calibrations obtained for different sensor distances from the blackbody suggests that the purge gas effect is not significant, and is within other experimental uncertainties. The agreement also suggests that the sensor's high-absorptance is gray because of different blackbody temperature ranges used to obtain the same heat flux level at the sensor.

The calibration of a heat-flux sensor over a period of time will show statistical variations because of experimental conditions that are difficult to control. Therefore, an uncertainty that indirectly accounts for purge-gas as well as other effects, based on long-term repeatability, is necessary. Several repeat measurements on the same reference sensor give a standard uncertainty value of 0.7 % for repeatability.

6.10 Combined uncertainty

Table 6 lists the individual uncertainties for different sources. The root-sum-square of individual uncertainties gives the combined uncertainty value u_c. The relative expanded uncertainty U, corresponding to a coverage factor of k =2, is about 2.1 %.

Table 5. Estimate of uncertainties in heat-flux sensor calibration [%]
(Heat-flux range 10 kW/m^2 to 50 kW/m^2)

Uncertainty Source	Type	Uncertainty
1. Transfer standard ESR (previous calibration)	B	0.60
2. Blackbody temperature	B	0.01
3. Blackbody emissivity	B	< 0.001
4. Blackbody aperture - radiation uniformity	B	< 0.001
5. Alignment (distance)	B	0.40
6. Alignment (angular)	B	0.06
7. Radiometer aperture size	B	0.05
8. Signal output: Radiometer	A	0.20
Sensor	A	0.20
9. Other sources: purge-gas, repeat tests	A	0.70
10.Relative expanded uncertainty ($U = ku_c$)	**k = 2**	**2.1**

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